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Technical Memorandum 1

VERY-HIGH-POWER VLF SYSTEMS

By: L. T. DOLPHIN, JR. A. F. WICKERSHAM, JR.

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Prepared for:

OFFICE OF NAVAL RESEARCH
WASHINGTON, D.C.
AND
ADVANCED RESEARCH PROJECTS AGENCY
WASHINGTON, D.C.

CONTRACT Nonr-4178(00)
ARPA ORDER NO. 463

STANFORD RESEARCH INSTITUTE

MENLO PARK, CALIFORNIA

*SRI

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SRI Project 4548

This research was sponsored by the Advanced Research Projects Agency as part of Project DEFENDER under ARPA Order No. 463.

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ABSTRACT

A novel technique for the generation of very high peak radio-frequency powers, suggested by Australian scientists in 1960, has been studied at Stanford Research Institute. The suggested technique combines transmitter and antenna into a single ring-shaped unit. Power is developed by charging a number of capacitors in parallel and discharging them in series. A 20 Mc working model was constructed at SRI and it was found to generate a clean, high-power, RF pulse. Radar returns from the transmitted signal are readily obtainable.

The basic ring transmitter technique appears applicable to VLF, and should provide pulse powers from megawatts to hundreds of megawatts, at least. CW operation of this device is a possibility. Because of the low cost of this technique, it is concluded that study and engineering testing should be undertaken to determine the practicality of achieving very high RF power at VLF.

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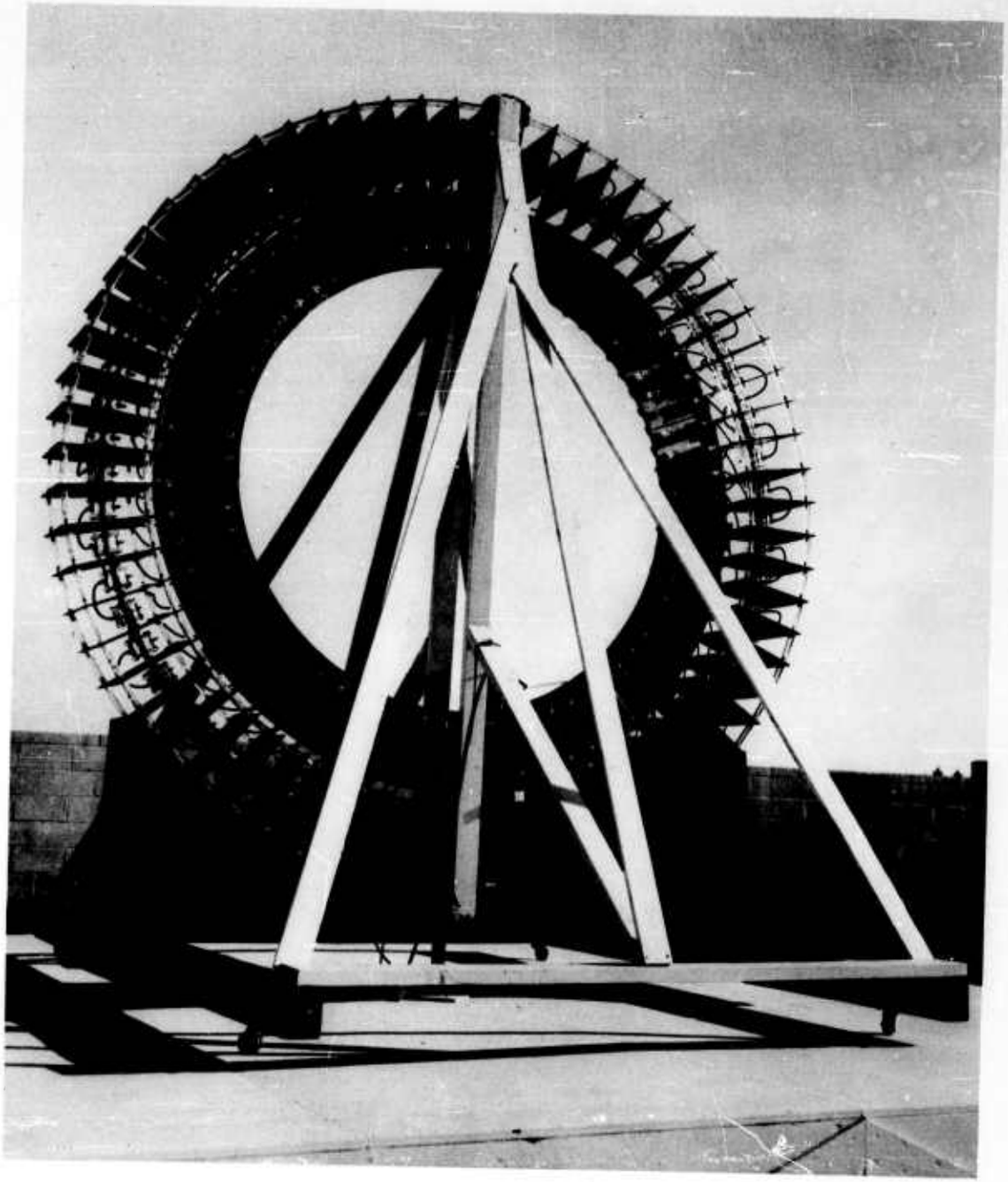


FRONTISPIECE A 20–Mc RING TRANSMITTER CAPABLE OF A 1 MICROSECOND PULSE WIDTH AT 10 MEGAWATTS PEAK POWER

INTRODUCTION

In 1960, Australian scientists under the leadership of Dr. Kurt Landecker proposed a novel scheme for the generation of very high peak power at radio frequencies.* Landecker's device combines transmitter and antenna into a single radiating unit in the form of a circular loop antenna, usually having a diameter of 0.2 to 0.4 wavelength.

Power is generated, not with conventional vacuum tubes, but by a method adapted from the familiar Marx impulse generator. Capacitors are placed in series in a circular ring, charged in parallel from a common power supply, and discharged in series. Peak powers of megawatts to thousands of megawatts can be obtained in this manner. Not only is the great expense of a conventional transmitter eliminated, but waveguides, coaxial lines, rotary joints, water cooling systems, exciters, and driver stages are unnecessary. The device radiates as a magnetic dipole antenna; this is inherently superior to an electric dipole with regard to corona losses and air breakdown problems.

In 18 months of research at SRI we have confirmed the soundness of the basic theory and the realizability of practical transmitters of this type. Our research under ARPA Order 463 and ONR Contract Nonr 4178(00) has shown that clean, well-formed, high-power pulses can be generated as proposed by Landecker, provided suitable high-speed switches are used to series-connect the charged capacitors in the ring. At the present time the high-speed switches found most satisfactory are triggered, pressurized, spark gaps. The use of moderate gas pressure (20-80 psi) in these gaps reduces spark losses and spark-channel formation time so that a high degree of synchronism in firing can be obtained. Ultraviolet-flash or magnetic triggering can be used to improve the firing speed of the gaps, and to control the firing time accurately to permit pulse to-pulse phase coherency.

---

* Landecker, K., and Imrie, K. S., "A Novel Type of High Power Pulse Transmitter," Aust. J. Phys., Vol. 13, p. 638 (1960).

Our experiments and studies have been carried out at 20 Mc, where the transmitter ring is only a few meters in diameter. It has been found that parasitic elements can be used with the ring to improve directional characteristics and control the pattern. Good radar returns have been obtained from nearby mountains and aircraft, and the radiated signal appears spectrally clean and free from serious spurious emissions.

Some experiments also have been conducted that indicate the Landecker ring may be useful at frequencies as high as several hundred megacycles, although realizable pulse widths are short at these higher frequencies.

A simple laboratory experiment has shown the possibility of extending the ring transmitter configuration to VLF frequencies. The possibilities of this device are so great at VLF that we believe every consideration should be given to their development. Applications to underseas communication are immediately obvious; in addition, the transmitter should be useful in conducting studies of the ionosphere and VLF phenomena. The cost of a practical ring transmitter is much lower than a conventional VLF system, and the possibilities Landecker has suggested are so intriguing, that this system may very well prove to be a major breakthrough in RF power generation.

In recent years there has been discussion of underground communication at VLF;* such possibility could provide communication with underwater vessels. While the naturally hardened site of an underground transmitter is desirable, knowledge of underground propagation conditions probably is too limited to risk the expense of an underground, conventional VLF transmitter; however, a Landecker type of ring transmitter could be installed underground at much less expense. A natural outcropping of suitable earth-stratum could permit a relatively shallow depth installation of a horizontal ring transmitter. The diameter of the ring need be only a third of the diameter of an above-ground ring because of the high dielectric constant of the earth. Such installation could provide a relatively low cost experimental arrangement for determining the feasibility of underground and undersea communication.

---

* IEEE Trans. on Antennas and Prop., Special Issue on Electromagnetic Waves in the Earth, AP-11 (3), May, 1963.

The purpose of this memorandum is to discuss and recommend research work that would prove and develop the Landecker transmitter at VLF. Specific studies of efficiency, bandwidth, modulation, peak power, and spurious and harmonic content should be made. Design and testing of a large-scale model are recommended.

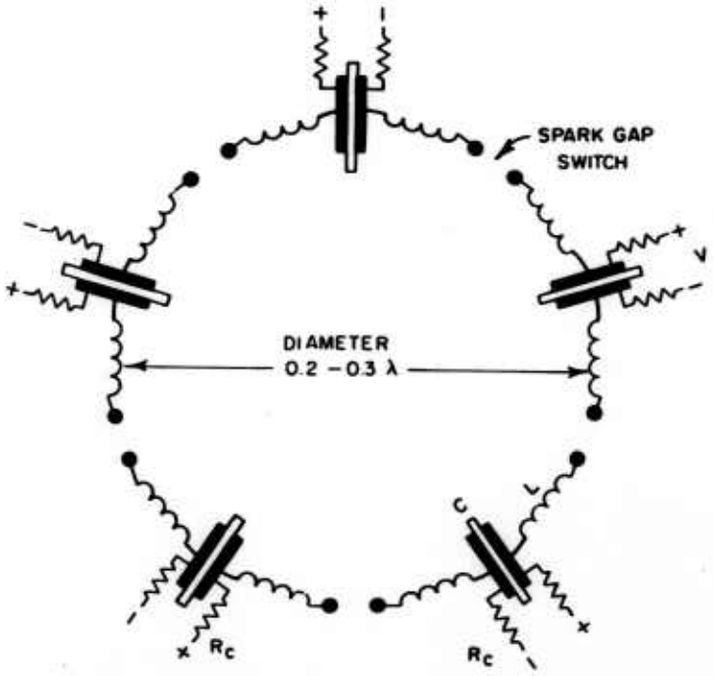
II BASIC THEORY OF OPERATION

The Landecker Ring Transmitter may be understood readily with the aid of a sketch of the basic configuration (Fig. 1) and a few simple equations. The (N) series capacitors tune the inductance (L) of the ring to the desired operating frequency. Losses in the circuit arise from the resistances of the fast switches (R_s) and the conductors, dielectric hysteresis, and the radiation resistance R. The radiation resistance is a function of ring diameter; typically, the radiation resistance is 10 to 50 ohms. The high-frequency-switch resistance is a few tenths of an ohm per switch; at low frequencies it should be less. The operating quality, Q, of the device usually will lie between 10 and 100.

The energy stored in the N capacitors, $E = 1/2NCV^2$, is discharged in a time, $\tau = 2.3Q/\omega$, where ω is the angular frequency. Thus the average power during a pulse will be $P = 1/2NCV^2 (\omega/2.3Q)$ watts. The pulse from the ring initially increases in amplitude, as the spark channels increase in temperature and size, and then decays nearly exponentially. The pulse shape may be modified and stretched by the use of one or more parasitic secondary rings electromagnetically coupled to the active ring. The above formulas for pulse length and power refer to a period from the beginning of the pulse to the time at which the power has decayed to 10 percent of its maximum value. Figure 2 is a plot of pulse length as a function of operating Q and frequency, assuming no pulse stretching.

The capacitors are charged from a common power supply through charging resistors (R_c) or charging chokes (L_c). If resistors are used, a maximum limit on the PRF is set by the charging time, $\tau_c = R_c C_i$ (seconds). If chokes are used, the ring may be recharged as soon as the fast switches, G, are quenched.

Peak pulse power depends largely on operating voltage and total capacitance, so it is desirable to use a large number of capacitors and a high charging voltage--perhaps as high as 150-200 kv--to obtain maximum power levels.



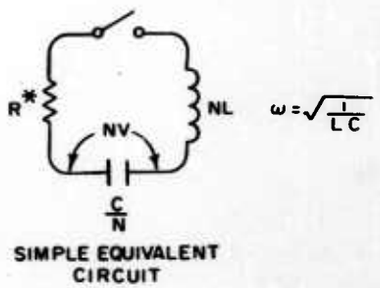


FIG. 1 SCHEMATIC DIAGRAM OF ELEMENTARY LANDECKER RING SPARK TRANSMITTER

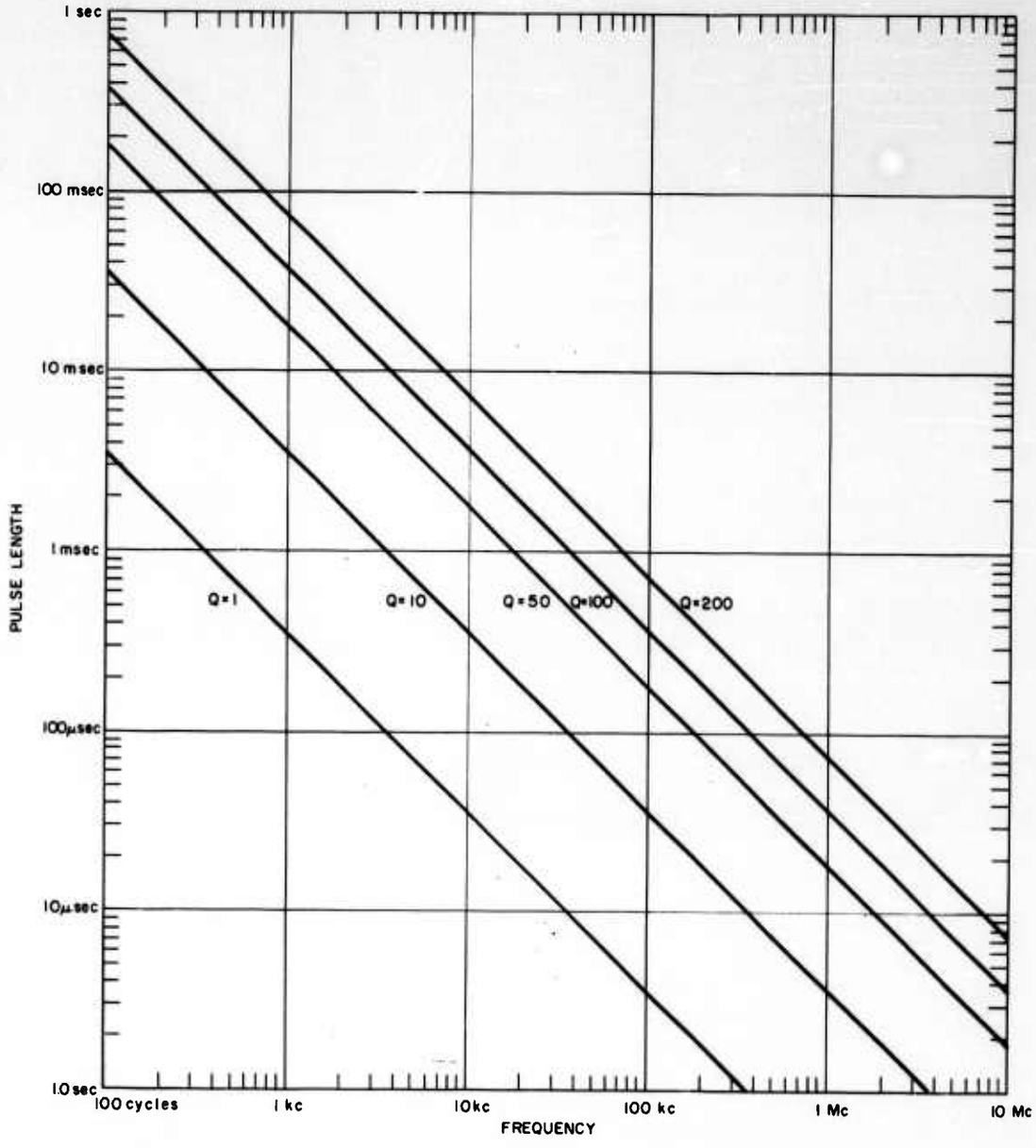


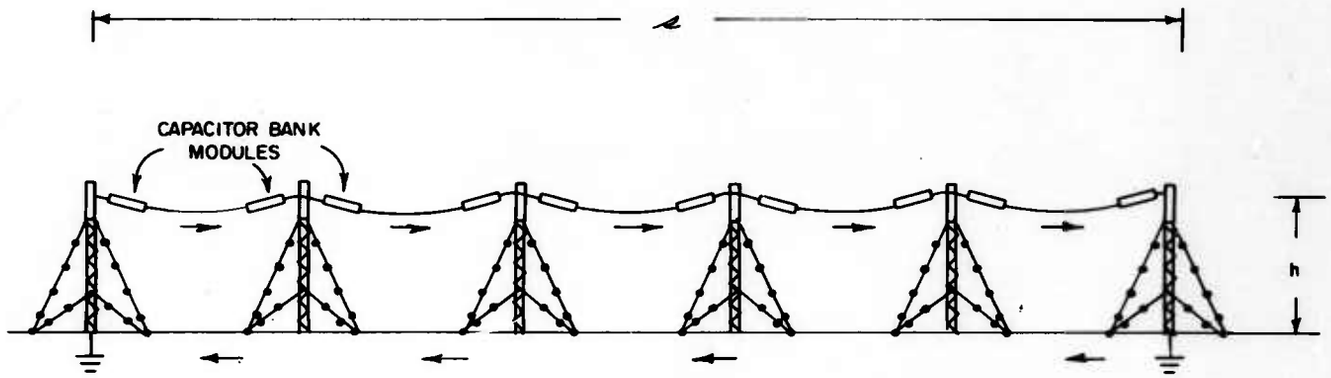
FIG. 2 PULSE LENGTH vs. FREQUENCY

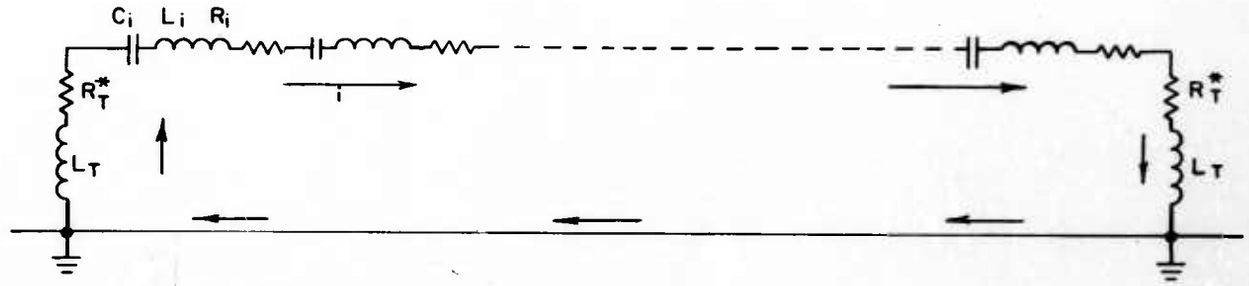
The entire ring structure, usually about 0.2 to 0.4 wavelength in diameter, constitutes a magnetic dipole antenna. Such an antenna is equivalent to an electric dipole oriented normal to the plane of the ring, with electric and magnetic vectors interchanged.

For VLF applications, a Landecker ring transmitter would be several kilometers in diameter. If mounted as a horizontal ring above ground, it would have poor radiation characteristics because of the closeness of the ground image. However, the ring can be cut in half and mounted vertically over a ground plane, as sketched in Fig. 3, to obtain relatively good pattern and radiation characteristics. In this case the capacitors can be grouped in modules located at each support tower (Fig. 4). In Figs. 5-9 we show the radiation pattern and radiation resistance for such a configuration. Vertical polarization is obtained and satisfactory performance can be expected.

Losses in the fast switches can be made small by using spark gaps pressurized in an inert atmosphere and by designing to avoid corona losses. The use of pressurized gaps decreases the gap spacing for a given charging voltage; thus a shorter spark channel is more rapidly formed. This means all gaps are broken down and conducting within a very small fraction of an RF cycle. With present techniques all switches can be closed and conducting within a few nanoseconds of time from the firing of the first gap.

The Landecker ring transmitter bears little resemblance to the spark wireless transmitter used before vacuum tubes. In contrast to the heavy interference and spurious emission from the old spark transmitter, the pulse radiated from a ring transmitter is relatively spectrally pure, when observed several kilometers away. Some electrostatic shielding may be desirable to reduce microwave radiation from the spark gaps in the near field because of the very high power levels. The spark gap is used in the Landecker transmitter--in preference to a vacuum tube, thyratron, or solid-state device--because of its high-voltage, high-current and low-loss capabilities.





$$L = 2L_T + NL_i$$

$$C = \frac{C_i}{N}$$

$$R = 2R_T^* + NR_i$$

$$\omega_o = \sqrt{\frac{1}{LC}}$$

EQUIVALENT CIRCUIT

FIG. 3 VLF TRANSMITTER SYSTEM

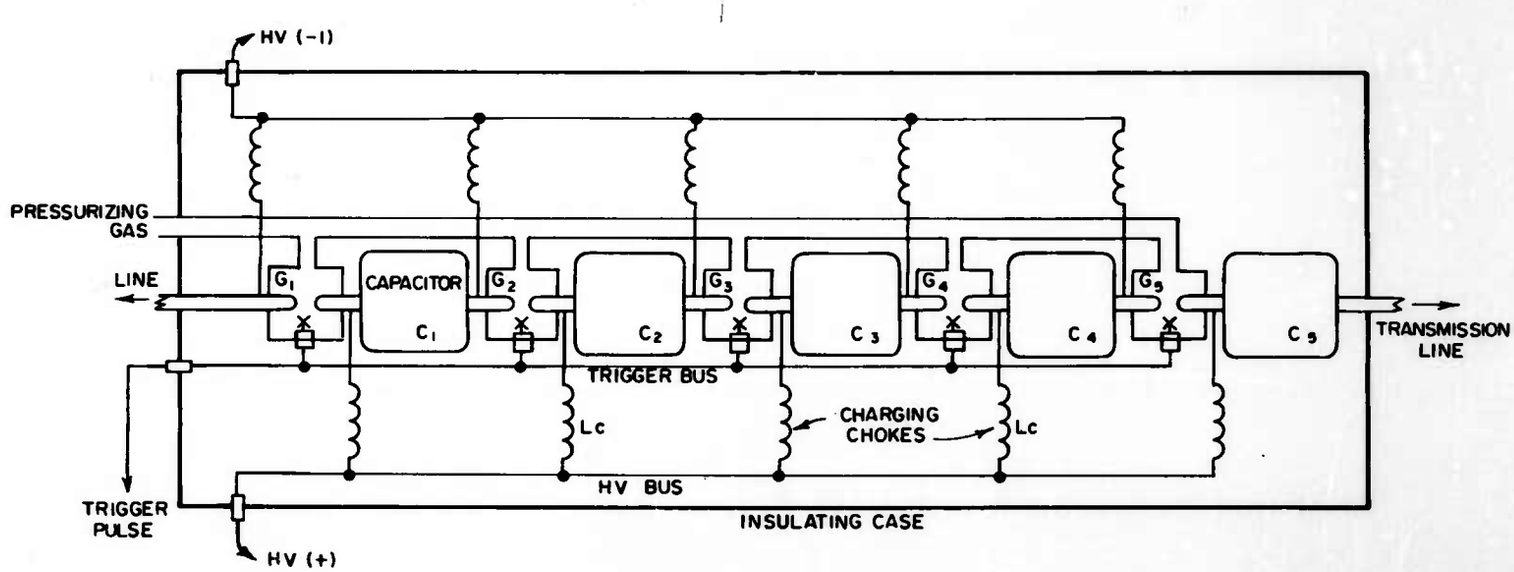


FIG. 4 DETAIL OF ONE CAPACITOR MODULE

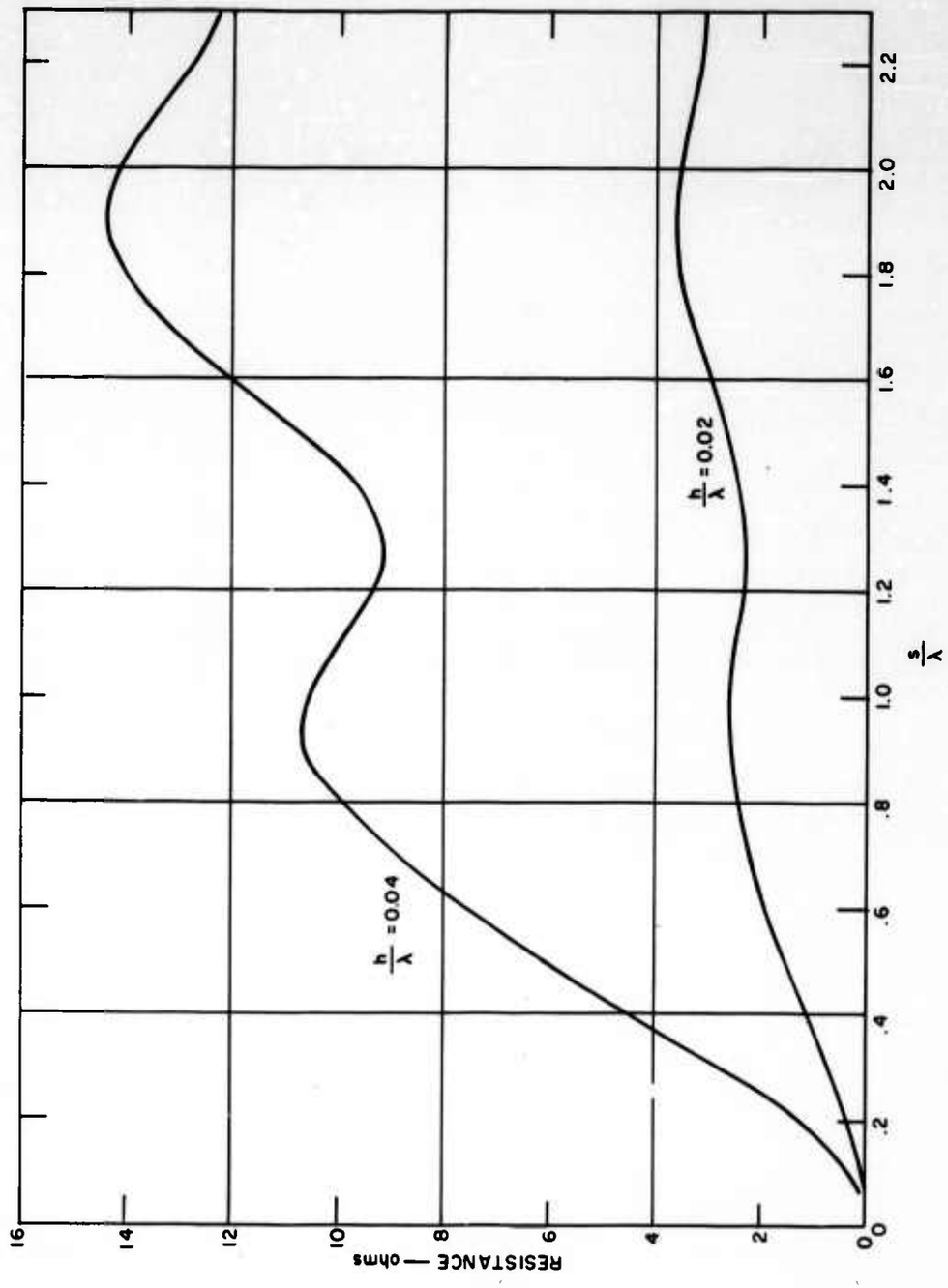


FIG. 5 RADIATION RESISTANCE OF A RECTANGULAR HALF LOOP OVER A GROUND PLANE

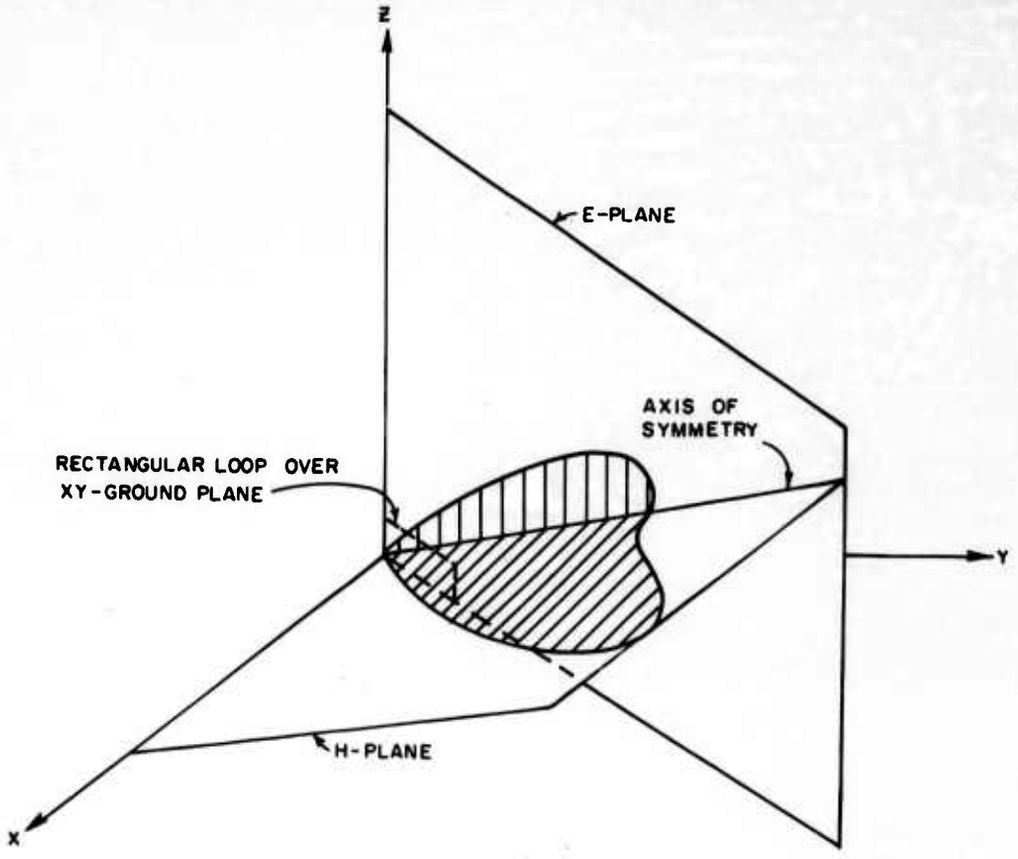


FIG. 6 VLF LOOP ANTENNA RADIATION PATTERN COORDINATE SYSTEM

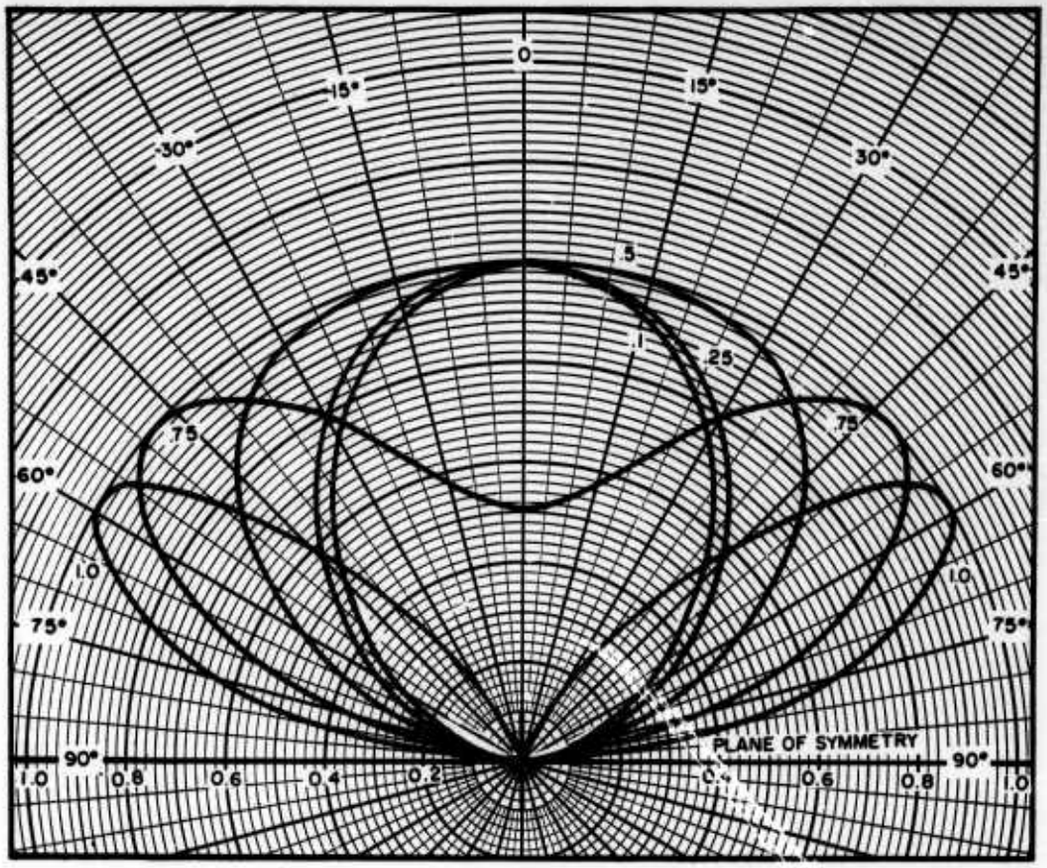


FIG. 7 H-PLANE RADIATION PATTERN, VERTICAL POLARIZATION, FOR A VERTICAL RECTANGULAR LOOP OVER A GROUND PLANE FOR VARIOUS DISTANCES OF SEPARATION OF THE VERTICAL SIDES, MEASURED IN WAVELENGTHS
(Height above ground is 10^{-2} wavelength in all cases)

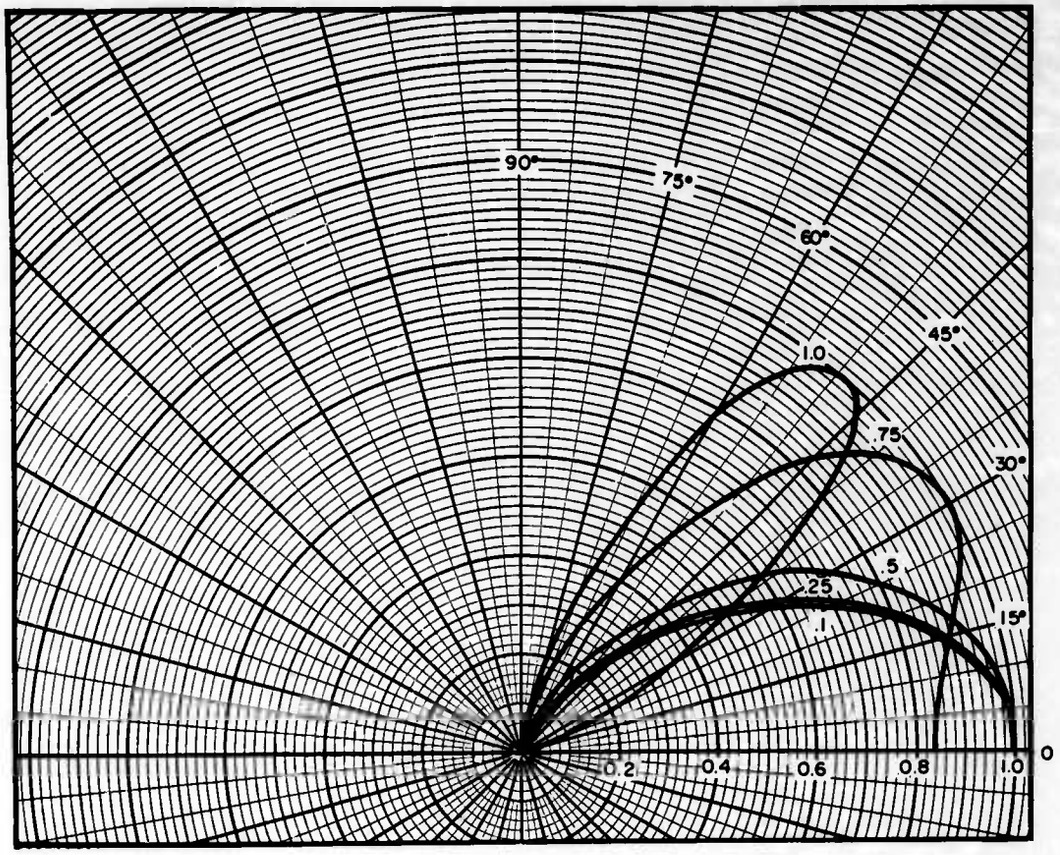


FIG. 8 E-PLANE RADIATION PATTERN, VERTICAL POLARIZATION, FOR A VERTICAL RECTANGULAR LOOP OVER A GROUND PLANE FOR VARIOUS DISTANCES OF SEPARATION OF THE VERTICAL SIDES, MEASURED IN WAVELENGTHS
(Height above ground is 10^{-2} wavelength in all cases)

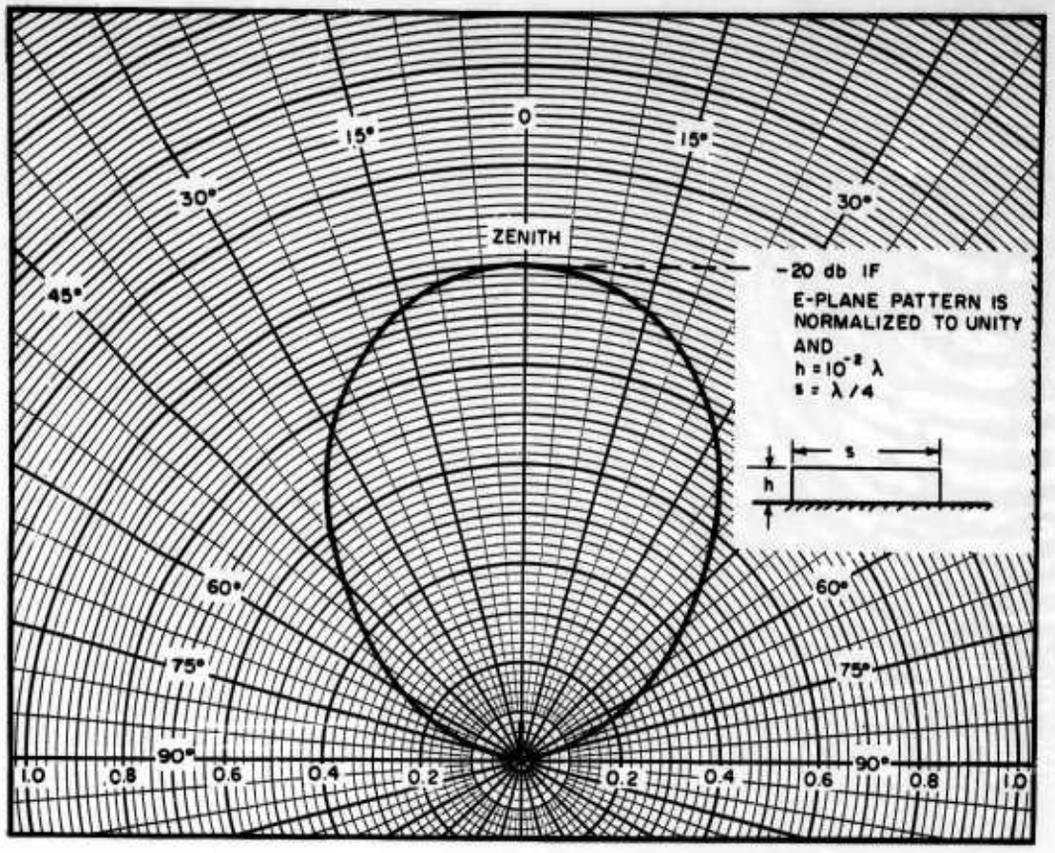


FIG. 9 H-PLANE RADIATION PATTERN, HORIZONTAL POLARIZATION, FOR A VERTICAL RECTANGULAR LOOP OVER A GROUND PLANE FOR VARIOUS DISTANCES OF SEPARATION OF THE VERTICAL SIDES, MEASURED IN WAVELENGTHS
(Height above ground is 10^{-2} wavelength in all cases)

III PULSE-TO-PULSE COHERENCE AND MODULATION

It may be desirable to fire the ring at a precisely controlled time and phase with respect to a master RF oscillator. At VLF this can be done with great accuracy by triggering the gaps from an auxiliary spark, which illuminates the main gap with a fast-rise UV flash. Alternatively, the gaps may be triggered by a magnetic pulse generated by a loop of wire around the gaps, a technique discovered and developed at SRI. With either triggering technique, the ring can be turned on at a precisely controlled time; thus, pulse-to-pulse coherence can be obtained by locking the trigger pulses to a stable oscillator.

The simplest way of applying modulation to the Landecker ring transmitter is to vary the spacing between pulses by means of the triggering circuit. This scheme requires no current-controlling modulator in series with the power supply lead. The minimum spacing between pulses can probably be reduced to zero by using a number of rings sequentially fired. Since a 30-kc system with a Q of 90 would have a bandwidth of about 330 cps, the information capacity of the system would be comparable to existing VLF systems.

The use of a secondary ring was suggested by Landecker's group as a means of stretching the pulse length and controlling the pulse shape. Landecker has reported good success with secondary rings to achieve these objectives.*

---

* Private communications.

IV DESIGN EXAMPLE

The following is an example of a VLF transmitter design, using the Landecker ring idea. The operating frequency is 30 kc (wavelength λ = 10,000 m), and the ring is a rectangular loop 0.04λ (400 m) high and 0.5λ (5000 m) long. From Fig. 5 we see the radiation resistance of such loop is 6 ohms. The inductance of the loop is 22 mh and requires a total series tuning capacitance of 1280 pf. The required capacitance is divided equally between 200 capacitors connected in series through spark gap switches. Each capacitor, 0.256 μf, is charged from a common power supply to a potential of 50 kv. When capacitors are fully charged the gaps are triggered, discharging all 200 capacitors in series; the total energy discharged is $1/2NCV^2$ = 62,500 joules.

The efficiency of the transmitter is the ratio of radiated VLF power to the total power discharged, and can be expressed as the ratio of radiation resistance to total resistance in the system. Each spark-gap switch can be expected to have about 0.2 ohm of resistance, giving a total switch resistance of 46 ohms. The ring reactance is 4150 ohms, so the operating Q will be approximately 90. The pulse width ($2.3\ Q/\omega$) is about 1 msec, measured to the 10-percent decay point.

The power discharged during the pulse is $(1/2NCV^2)(\omega/2.3Q)$ = 45 Mw, and since the transmitter has an efficiency of 7.7 percent, the power radiated is 3.9 Mw. Further power increases are possible by adding more capacitors, which rapidly increases the stored energy.

The strong dependence of radiation resistance on antenna height has led us to choose high support towers in this example, in order to realize an efficiency of 7.7 percent. While the antenna is somewhat larger than the top-loaded vertical used in VLF installations, it is simple and relatively inexpensive in construction, has a higher efficiency, and requires no impedance matching. We have retained the simple and desirable features of the Landecker ring in that there are no feeding and matching problems.

The efficiency, principally a function of radiation resistance and spark gap resistance, might possibly be improved by lower spark gap resistance at VLF.

Since the loop is greatly elongated, most of the radiation occurs from the two end towers and is vertically polarized. A coordinate system for describing the radiation pattern of a VLF loop over a ground plane is shown in Fig. 6, and principal plane radiation patterns are shown in Figs. 7, 8, and 9.

V SUMMARY

The Landecker ring transmitter has promise as a means of generating very high pulse powers at VLF. The simplicity and very low cost of building such a device makes it especially attractive. Power levels of hundreds or thousands of megawatts appear feasible, and long pulse or even CW operation may be achievable. For these reasons we recommend that additional research be undertaken in the VLF range so that the technique can be evaluated.

While the ideas and concepts of a VLF transmitter modelled after the ring transmitter of K. Landecker are both simple and straightforward, the engineering and development of practical working models requires time and careful study. For this reason it would be unwise to proceed immediately with a full-scale field model. Although we believe a practical device can be built, we recommend first a preliminary study and investigation, with emphasis on the verification of theory and the realization of a practical working model VLF ring transmitter to include: a study of high-current, low-impedance switches and spark gaps at VLF, including gap losses and quenching time; design, modelling and testing of antennas from the standpoint of radiation patterns and radiation resistance; a study of pulse shape, spectral characteristic and spurious radiation from a pilot model VLF transmitter; CW operation; and design and construction of a large, scale model VLF transmitter using simple support towers and a minimum number of capacitors to evaluate near and far field performance, radiation patterns, power output, interference problems, and pulse shape.

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